STRV-1d QWIP Technology Validation in Space Flight[1]

James T. Kenny
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109
818 354-3719
James.T.Kenny@jpl.nasa.gov

Harold R. Pollock
Jet Propulsion Laboratory[2]
(909) 593-3581 x4202
pollock.randy@orbital.com

Abstract — New technologies are arriving on the scene that promise enhancement or new capabilities. Some of these technologies have potential for NASA and DOD space-based applications. In these cases, the technology must be demonstrated and validated to a degree that risk may be balanced for the space mission roles. Quantum Well Infrared Photodetector (QWIP) is one of these technologies. QWIP has a variety of space-based applications in the 8 to 16 μm wavelength range. Radiation tolerance and higher operating temperature are potentially significant benefits for long duration missions. In this paper, we describe the selection of and preparation for a mission that provides the opportunity to demonstrate and validate QWIP FPA in the natural, space radiation environment. We discuss the objectives of this demonstration opportunity, and the development and test steps required to deliver the QWIP Experiment to space.

Table of Contents

Introduction

Space exploration and space-based surveillance applications require high performance, large format, long-wavelength infrared (LWIR) detector arrays in the 8 μm and longer wavelength range. Thus, NASA and the Ballistic Missile Defense Organization (BMDO) have supported significant efforts developing highly sensitive infrared detectors and large format focal plane arrays (FPAs) based on the artificial low effective band-gap semiconductor material systems such as GaAs/AlGaAs {1}, {2}. The Jet Propulsion Laboratory (JPL), California Institute of Technology, under contracts from NASA and BMDO, have optimized GaAs/AlGaAs based multi-quantum wells for infrared detection. Optimized detector design, light coupling schemes and large format FPA fabrication and packaging have brought the QWIP technology to successful demonstrations. The current QWIP technology enables fabrication of large arrays, provides long term stability of responsivity, and operates at wavelength longer than 15 μm at 40 Kelvin. These characteristics complement and extend HgCdTe sensor technology and provide significant incentives to validate the technology for space-based applications, especially strategic surveillance. In this paper, we discuss the design of a space flight experiment designed to demonstrate and assess QWIP FPA uniformity, stability, and repeatability in a space environment.

Experiment Objective

The objectives of the QWIP Experiment aboard the Space Technology Research Vehicle 1d (STRV-1d) is to demonstrate and assess QWIP FPA uniformity, stability,

---

[1] 0-7803-6599-2/01/$10.00
[2] Mr. Pollock is now at Orbital Sciences Corporation, 2771 North Garey Avenue, Pomona, CA 91767

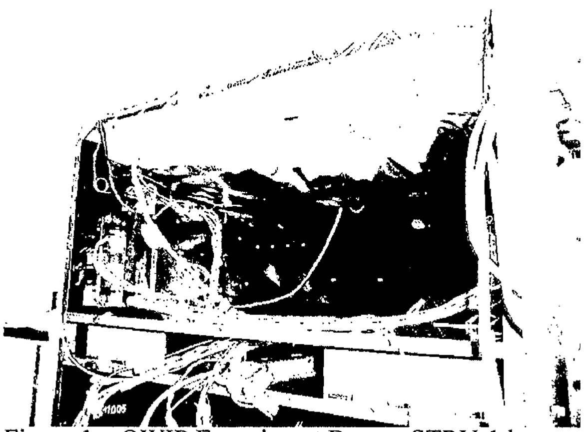

Figure 1 – QWIP Experiment Bay on STRV-1d

and repeatability and responsivity in a space environment; in particular the radiation environment. Measurements of photo current and dark current changes for the individual pixels of a hybridized 125 x 125 GaAs/AlGaAs QWIP FPA are made. These current measurements are compared to determine the FPA spatial uniformity, the FPA stability during an experiment cycle, and the FPA repeatability over the one year mission.

Success Criteria

The success of this flight experiment is determined by its ability to measure dark current and photo current, and their relative spatial and temporal changes during the mission, and relate those changes to the total radiation dose received in the detector. The following definitions of dark current, photo current, and experiment terms are used in the conduct of this experiment.

(1) Dark-current is generated when electrons "boil" out of the wells without illumination of the detector. In QWIPs, this process is a strong function of focal plane temperature.
(2) Photo-current is generated when photons excite electrons out of the wells and into the conduction band. It is the additional current created by the illumination of a detector.
(3) Frame is a single measurement of each pixel on the focal plane.
(4) Cycle is all of the data collected during a single operation of the experiment.

With these definitions, the detector uniformity, stability, and repeatability, or their derivatives, shall be measured to the following criteria.

Spatial non-uniformity of dark and photo current shall be determined, for each frame, with an uncertainty of less than 1% of the average.

Temporal current stability of the mean dark-and photo currents per frame shall be determined with an uncertainty of less than 1% per minute for each cycle. These current determinations shall be established for three blackbody target temperatures.

Temporal current non-repeatability (long term instability) of the mean dark and photo currents per cycle shall be determined with an uncertainty of less than 1% per week. These current determinations shall also be established for three blackbody target temperatures.

Responsivity non-repeatability (long term instability) of the mean responsivity per cycle shall be determined with an uncertainty of less than 1% per week.

Mission Design

The primary mission requirements used to select a host spacecraft were (1) a minimum of one year in-space operation, and (2) high proton and electron radiation exposure. Using this criteria, the STRV-1c/d Mission was selected to host the QWIP Experiment.

The STRV-1d spacecraft is one of two spacecraft developed by the DERA (the Defence Evaluation and Research Agency) for this Mission. DERA is an Agency of the UK Ministry of Defence (MOD).

Both spacecraft are launched from the Ariane 5's ring-shaped ASAP 5 (Ariane 5 Structure for Auxillary Payload) platform. ASAP 5 enables Arianespace to accommodate small auxiliary satellites in addition to the Ariane 5's primary payload. The two STRV-1 spacecraft weigh approximately 100 kg each.

STRV-1 launches to a geosynchronous transfer orbit (GTO) 620 km by 36,000 km at 7.5 degree inclination. This orbit provides four transitions through proton and electron belts each orbit. The one-year mission has the potential for over 100 Krad total dose radiation.

Instrument Design

The experiment consists of three major components: 1) the integrated dewar assembly (IDA) which includes the cryocooler, 2) the blackbody assembly and 3) the electronics.

The QWIP Experiment was installed in an experiment bay of the STRV-1d spacecraft (Figure 1). The IDA and blackbody assembly are installed on the bottom side of the spacecraft top deck and covered with a thermal blanket. The electronics chassis will be mounted to the lower equipment deck directly beneath the IDA and Blackbody.

It is important to note that since this experiment is only looking at the focal plane performance, there is no external view to space or any other object. The blackbody flood illuminates the focal plane with no imaging optics required.

Integrated Dewar Assembly

The Integrated Dewar Assembly (IDA) contains the QWIP focal plane in an evacuated titanium dewar integrally mounted to the cryocooler. The low inertia, high thermal isolation design allowed a DRS (formally Texas Instruments) 1 Watt tactical cryocooler to cool the focal plane from room temperature to 50 Kelvin in under ten minutes.

The dewar contains a motherboard (Figure 2 integrated circuit (ROIC). The back of the motherboard is bonded to a thermal plug that mates with the cryocooler cold finger. This plug is larger than the FPA to ensure that temperature gradients are minimized.

Over a portion of the FPA, a "bridge" is mounted (Figure 3). It serves two purposes. First, it provides a cold view to about 25% of the focal plane to allow a measure of dark current. Second, it is the mount for two "QWIPette" sensors. These are individually readout super detectors to allow drifts in the ROIC circuits to be isolated from changes in the QWIP detector material.

On one end of the QWIPette material, four detectors are combined in parallel and covered with an epoxy that is opaque in the infrared. These measure dark current. The other end has two detectors in parallel to provide a measure of the responsivity. The four versus two detectors were selected to provide roughly equal output current to the readout electronics and thus allow identical offsets and gains to be used.

Over the focal plane, a very light-weight cold shield provides radiative decoupling of the dewar walls and the detector area (Figure 4). The aperture of the dewar is bare germanium window. No anti-reflection coating was used to avoid radiation degradation that could potentially cause a change indistinguishable from a quantum efficiency change in the detectors.

The dewar was integrated directly with the cryocooler cold finger to minimized the heat load and increased thermal path associated with other techniques.

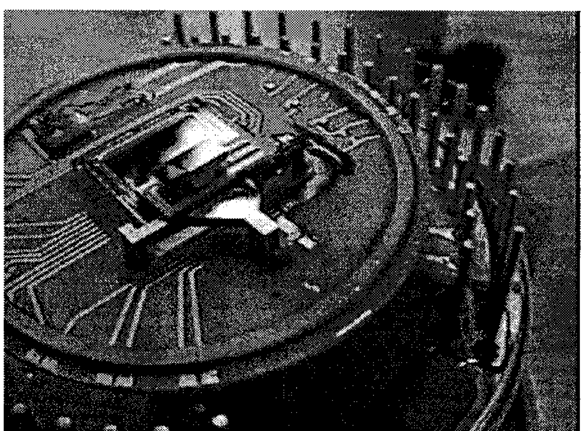

Figure 2 – Focal plane mounted on motherboard.

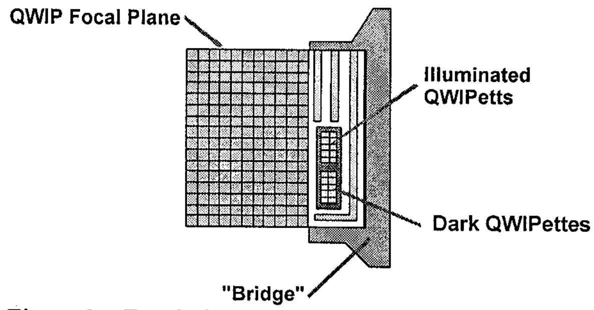

Figure 3 – Focal plane mounted on motherboard.

Blackbody Assembly

Directly in front of the dewar window, a resistance filament blackbody is mounted. The blackbody mounting bracket is attached to a passive thermal radiator so that its non-operating temperature is approximately 250 Kelvin. A small gold coated Mylar sheet wraps around a lip surrounding the blackbody and the dewar to prevent stray light from entering the dewar window.

Passing a precise current through ~~it~~ the blackbody filament controls the blackbody's temperature. Small variations in the temperature across the filament are not important since there are no imaging optics in the system.

Electronics

The experiment's electronics consist of four major functional units in addition to power supplies and filters. These are 1) the command and data handling system, 2) the digital system, 3) the analog system and 4) the cryocooler controller. All of the units are housed in a common chassis.

The command and data handling system (C&DHS) acts as the conductor for the other systems. It communicates with the spacecraft, runs the scripts to sends time or event driven commands to the digital and cryocooler electronics, and monitors the other systems to ensure that no potentially damaging events can occur. Every 15 seconds, it generates a status report with mode information and key telemetry.

The digital system controls the low level operations of the

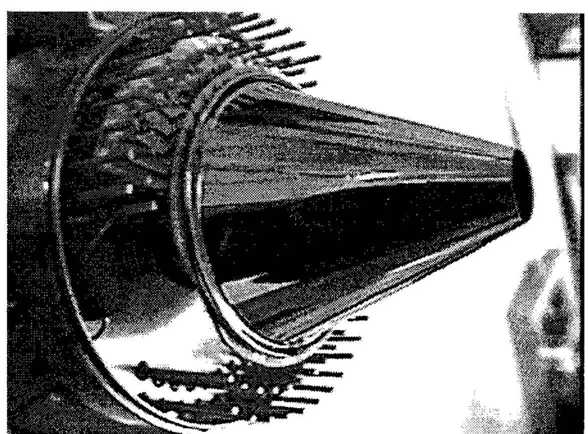

Figure 4 – Cold Shield installed over focal plane

focal plane signals (clocks, biases, etc.) and digitizes the data for transfer to the C&DHS (for eventual transfer to the spacecraft).

Due to the critical nature of some operations, the C&DHS and digital system each have their own microcontroller that run independently. The digital system runs a very small closed loop routine with critical timing requirements.

The support electronics were designed to be radiation tolerant. Electronic parts radiation tolerant to 50 Krads or greater were selected. Where inherent parts radiation tolerance was less than 50 Krads, local shielding was integrated around those individual parts. Data storage in DRAM used triple storage and majority vote process to avoid bit flip errors in the data.

Since the objective of this experiment was to determine the radiation effect on QWIP FPA characteristics, a radiation dose monitor chip was integrated on the FPA mother board. The radiation monitor, designated RadMon, is a RADFET, about 1 mm x 1 mm, mounted to a mother chip that is 1.8 mm x 2.2 mm in size.

Operational Scenario

Every few days the spacecraft turns on the experiment. The basic steps in an operation run are self test, cool down, collect data and transfer data to the spacecraft. Several key parameters are stored in Parameter Random Access Memory (PRAM). These include operational temperature, several delay timers to allow for FPA/blackbody stabilization, the integration time and the number of frames for each blackbody setting.

Once power is applied, the C&DHS performs a series of self-tests; most important of these are a memory check and the checksum performed on the code loaded into the PRAM. Memory errors are reported in the telemetry, but no attempts if made to avoid using that location. An error in the PRAM checksum results in further operations using the code loading into the Read Only Memory (ROM). After this check is complete, the C&DHS sends a code update to the digital system which does not have its own PRAM.

After the self test is complete, the experiment prepares its first status packet . Two minutes after power is applied, the spacecraft checks to see if this packet is ready. If it is, then the spacecraft synchronizes the internal clock to the spacecraft time and sends the command to start the cool down cycle. Note that the spacecraft does not inspect the contents of the status packet for errors since there is nothing that could be done to address anything autonomously. Also, the experiment has numerous voltage/current limiting circuits and software controlled cut-outs that protect the hardware from damage.

After receiving the cool down command, the cryocooler is turned on. During the cool down cycle, a status packet is prepared every 15 seconds. Key parameters include the focal plane temperature, the cooler status (on/off and cool down/regulation), the FPA bias status, the blackbody status (off/low/high) and the QWIPette current (if bias is applied).

When the cryocooler is turned on, a count down timer is set within the C&DHS. To help protect the spacecraft batteries, a limit is placed on how long the cooler can run before collecting data. Once the FPA has reached the set point, this timer is set down to a shorter delay to allow the FPA temperature gradients to stabilize (nominal delay is 2 minutes). If the remaining time on the original timer is less than this delay, then it is not changed.

When this timer expires, the C&DHS starts to request frame data from the digital system. The basic sequence of frame settings is (with nominal number of frames in parentheses):

(1) Bias is turned off to collect ROIC background noise (5)
(2) Bias is turned on with the blackbody at ambient temperature – roughly 250 K (5)
(3) The blackbody is set to 320 K (12)
(4) The blackbody is set to 380 K (12)
(5) The blackbody is turned off (6)

Between each change in blackbody temperature, the next frame is delayed 2 minutes to allow all of the temperatures to stabilize. The final frames are used to verify that the blackbody has not warmed its assembly during the higher settings.

After all frames have been collected and stored in the C&DHS buffer, the cooler is shut down internally and the spacecraft is notified that the data are ready. The spacecraft retrieves them and stores it in its recorder for eventual downlink to the ground.

The nominal sequence is shown in Figure 5. Better than anticipated cooling performance has allowed us to increase the delay between blackbody settings without increasing the total run time.

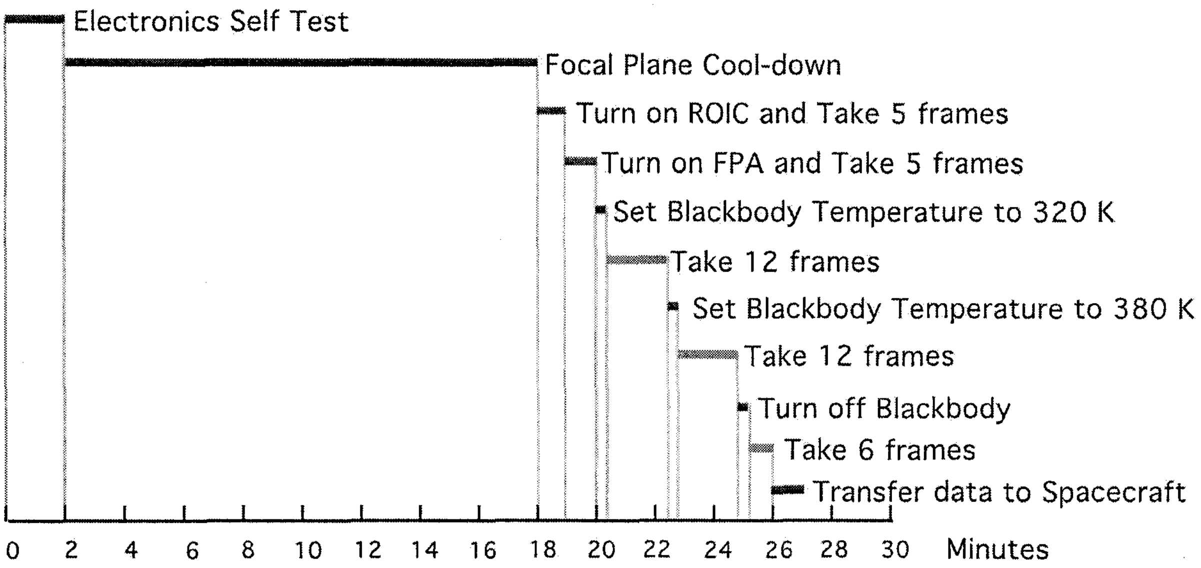

Figure 5 – Nominal QWIP Experiment Operation Timeline

Data Analysis

To answer the three basic questions that this experiment is designed to address (uniformity, stability and repeatability), we have developed the following data analysis techniques.

Uniformity

Since we are really trying to measure the change in uniformity as a result of the exposure to radiation, a standard offset and gain correction is applied to each pixel. This corrects for any variations in illumination, offsets and gains in the ROIC and analog to digital converters and any initial non-uniformity present in the FPA (which could be measured on the ground). Once this correction has been applied, changes in uniformity can be characterized by taking the standard deviation of each frame over the average response.

The spatial non-uniformity of dark current and photo current shall be determined for set of frames with the same blackbody temperature. All of these frames are averaged together to reduce the influence of system noise on the measurement of the non-uniformity. The value is calculated by:

$$\Psi = \sqrt{\frac{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}{n(n-1)}} \Bigg/ \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

where:

- Ψ is the non-uniformity of frame x
- x_i is the current (dark or photo) of the i-th pixel.
- n is the number of pixels 'x'

If all values of x_i are equal (i.e. the focal plane is perfectly uniform), then Ψ_x is 0.

Instability

To measure stability, we average all pixels that are identified as dark pixels or photo pixels (i.e are they under the bridge or not). All the pixels in each set are averaged together to provide a single frame measurement. The slope of current as a function of time is calculated by:

$$m_x = \frac{n\sum_{i=1}^{n} x_i t_i \cdot \sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} t_i}{n\sum_{i=1}^{n} t_i^2 - \left(\sum_{i=1}^{n} t_i\right)^2} \qquad (1)$$

where:

- m_x is slope of x
- x_i is the current (dark or photo) of the i-th frame.
- n is the number of frames 'x'
- t_i is the time the frame was taken (in minutes)

This calculation is completed for three blackbody settings, the ambient (both before and after), the low setting and the high setting.

Non-repeatability

Non-repeatability is measure in much the same way as the instability, except that we are now comparing the average of all frames of a given blackbody setting from one cycle to the next. Time is now given in weeks rather than minutes.

Conclusions

The STRV-1 spacecraft were successfully launched into GTO on November 15, 2000. Early checkout of spacecraft and QWIP Experiment indicate all systems are operating nominally. The QWIP Project is looking forward to an Experiment operation on ever sixth orbit for the next 12 months.

Acknowledgements

The space flight experiment described in this paper is being performed by the Device Research and Applications Section and the Space Instruments Implementation Section of the Jet Propulsion Laboratory, California Institute of Technology, and sponsored by the Ballistic Missile Defense Organization/ Materials, Structure and Power Technology Office. The authors are grateful to Dr. John Stubstad and Major James Shoemaker of the Ballistic Missile Defense Organization for their support of this project.

References

[1] W.R Dyer and D. Duston, *Long Wavelength Infrared Detectors and Arrays*: Phys. Appl. V, vol. 97-33, pp. 1-13, 1997.

[2] S.D. Gunapala and K.M.S. V. Bandara, *Physics of Thin Films*. New York, NY: Academic, 1995, vol. 21, pp. 113-237.

Biography

James T. Kenny is a Project Manager in the Space Instruments Implementation Section at the NASA Jet Propulsion Laboratory, California Institute of Technology. He has developed and led development of space hardware at Martin Marietta Corporation and Jet Propulsion Laboratory. He has a MS in Solid Mechanics from Colorado State University and a MS in Computer Information Systems from the University of Denver.

Harold (Randy) Pollock recently joined Orbital Sciences Corporation as a Program Manager and Space Instrument System Architect. He served as manager or system engineer on several flight instruments while at JPL, primarily in the infrared. Before joining JPL, he was a systems engineer on the Atmospheric Infrared Sounder at Lockheed Martin Infrared Imaging Systems in Lexington, MA. He holds a BS in Engineering and Applied Sciences from the California Institute of Technology.